HUMAN VISUAL RESPONSE TO NUCLEAR PARTICLE EXPOSURES

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Shortly after Roentgen's initial discovery of X rays it became known that these radiations can cause a sensation of diffuse light when they impinge on the retina of dark-adapted human subjects. When, in the course of the historic lunar Apollo 11 flight astronauts Neil Armstrong, Edwin Aldrin, and Michael Collins first experienced sensations of streaks and flashes of light it was not immediately clear that these visual phenomena were caused by radiation, as there are many modes of stimulating the visual apparatus. Visual sensations can be caused by mechanical, electric, magnetic, X-ray, and nuclear particle stimulation of the eye (1) as well as by direct brain cortex stimulation (2), and psychological states. Thus it is necessary to perform careful experiments in space and on the ground to fully account for each of the various light phenomena that have now been observed with some regularity by each of the crew members of four different lunar flights -- Apollo 11, 12, 13, and 14, and as recounted by Astronaut Philip Chapman at this Symposium (14).

Astrophysicists Fazio and others (3) have theorized that observation of light flashes in space might have been due to Cerenkov emission of light from primary cosmic ray particles. Earlier one of us predicted (4) that heavy primary cosmic ray particles traveling at any velocity could cause the appearance of light flashes due to dense ionizations and excitations in human tissue. At that time we emphasized the importance of investigating the biological effects of such particles.

Several categories of phosphenes are observed by the dark-adapted subjects in radiation exposures at ground level or in space flight. These include:

- Flash: very brief white star-like events or events with short tails(comma shaped),or flashes of undiagnosed shape.
- Streak: luminous, usually straight line of light, often giving a sense of rapid motion.
- Supernovae(a name coined by the astronauts): bright, rapid flash surrounded by halo and minor flashes.
- Luminous cloud: impression of light behind a small cloud formation or summer atmospheric electrical discharge over the horizon.
- Grey phosphene: grey-blue or grey-green faintly luminous background encompassing a major portion of the visual field.
- Sunrise phosphene: yellowish and rosy luminous background resembling early phases of sunrise in a clear sky.

Since none of the flash-type events has been seen by astronauts when they were in orbit under the solar radiation belt, or by us at ground level while dark-adapted in a natural cosmic radiation background, or in airplane flights up to 10,000 meters, we reasoned that relativistic singly charged particles - e.g.protons, mesons, or electrons- are unlikely to have caused the bright light flashes and streaks observed in space. These observations and the low photon yield from these particles argue against Cerenkov radiation from protons, mesons,or electrons as an important mechanism for this phenomenon. The only observation contrary to this statement of which we are aware is by D'Arcy and Porter, who have reportedly observed light flashes from μ mesons when cued with clicking sounds synchronized with the arrival of particles at an appropriately positioned coincidence counter telescope(5). (This experiment,to our knowledge, has not been substantiated by others.)

It seems more likely to us that heavily ionizing particles, including slow protons, might be capable of causing flash events when they cross the eye or some other part of the nervous system involved in the process of vision. Our first experiments were a test of the visual effects originated by very fast neutrons of 640-MeV peak energy, because these, by collision with atomic nuclei in tissue, produce heavily ionizing spallation recoils. This fast neutron beam also can generate recoil protons of sufficient energy for Cerenkov light, greater than the minimum required of about 470 MeV.

These experiments were reported in June 1970, at the International Congress of Radiation Research in Evian, France(6,1). Figure 1 of Reference 1 shows the manner in which forward neutrons from the interaction of 640-MeV protons with beryllium were utilized. Great care was taken to eliminate all stray radiation. The dark-adapted subjects reported seeing 25-50 luminous, white rapid flashes over their entire visual field when the eyes were exposed to a neutron flux from either the forward or the lateral direction. These observations established our ability to see local light events originating from ionizing events associated with nuclear interactions in the eye region. The exact location or the actual mechanism of the interaction was not established, however.

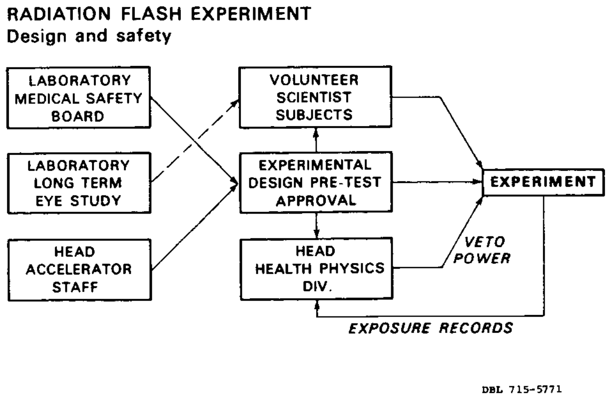


Figure 1: Design of experiments to ensure safety.

It was important to determine what contribution Cerenkov radiation made to our fast neutron beam observations, as some protons were traveling faster than the Cerenkov minimum. Fremlin, during activation analysis at neutron energies less than 8-MeV reported having seen light flashes(8). We extended our observations to fission neutrons and neutrons of energies less than 25-MeV with Bichsel at the University of Washington 60-inch cyclotron(10). The current status of these observations and other relevant experiments with X-ray and electrical phosphenes is shown in Table 1.

Radiation phosphenes fall into two distinct classes. The first class consists of local flash and streak phenomena. These include, in addition to some of the radiations encountered in space, fast neutrons of less than 25 MeV energy and neutrons of higher energy, observed at a flux density of 10^4 to $10^5 cm^{-2} sec^{-1}$. In the University of Washington exposure at neutron energies less than 25 MeV, the Cerenkov effect as the cause of light flashes is definitely excluded, since these particles and their secondaries travel much too slowly to produce Cerenkov light (10).

The second group consists of diffuse luminous clouds or greying of an otherwise dark visual field instead of highly local visual events. X-ray, electrical and magnetic phosphenes fall into this class. Eye exposure to Californium-252 at a flux density of $10^5 cm^{-2} sec^{-1}$ resulted in a persistent greying of the visual field which could have been due to phosphorescence or to distributed ionization from the abundant proton recoils. X-ray phosphenes are distinguishable from the heavy-particle phosphenes by the fact that X-ray phosphenes are not seen unless the dose rate is higher than about 24 millirads per second whereas we have seen neutron-induced phosphenes at dose rates of 0.1 millirad per second.

At this point it is important to detail the manner in which human experimentation with radiation phosphenes must be carried out. In view of the ability of radiation to induce manifold deleterious effects, including formation of cataracts and retinal degeneration, the utmost care is essential to keep doses at minimal levels. Figure 1 shows how we cope with this problem. The subjects are volunteer, mature

TABLE 1

Source	Mechanism	Flux Density	Response	Reference
Mechanical	Probably retinal membrane distortion	Finger pressure to eye ball	Diffuse, sometimes colored, visual patterns	(9)
Electricity	Induced action potential	0.3 mA	Brief, diffuse flashes, sometimes colored	(9)
Magnetic gradients	Action potential from induced EMF	1000 gauss/cm	Brief diffuse flashes sometimes colored	(9)
X-rays	Ionization and electronic excitation	$\geq$ 24 milliroentgen/sec	Diffuse light flood, left	(1,9)
Fission neutrons ^{252}Cf	Ionization by proton recoils and alpha from (n,α)	$10^5 n\ cm^{-2} sec^{-1}$	Greying of visual field. One tear-drop flash	(1,10)
Neutrons (ave. 3 MeV)	" "	$10^5 cm^{-2} sec^{-1}$	Short streaks and flashes	(8)
Neutrons (ave. 8 MeV)	" "	$10^4 - 10^5 cm^{-2} sec^{-1}$	White streaks and flashes with motion sense	(10)
μ-Mesons	Ionization or Cerenkov	Cosmic ray	Coincidences of undefined visual phenomena	(5)
Pions (1.5 BeV/c)	Ionization or Cerenkov	$200\ \mu\ cm^{-2} sec^{-1}$	No visual response	(1)
Mesons, protons and cosmic particles at 10,000 meters	Ionization of Cerenkov	3,1 hr. observing periods. 35°N and 50°N	No visual response	(1)
Helium ions	Ionization	1 to 100 sec^{-1} through posterior retina	Discrete brief flashes and streaks equivalent to 1-mm image on the retina. Motion sense	(present paper)
Cosmic rays	Ionization or Cerenkov	$\sim 1 cm^{-2} min^{-1}$ ($Z \geq 6$) light and heavy particles $\sim$ 12-25 mr/day	Various types of light flashes including long streaks	(14)

scientists, who have technical familiarity with radiation physics and radiation biology. A local responsible medical group previews the experiments, and those in charge of each accelerator facility agree to the protocol in advance. The health physicist in charge carries out independent measurements, is present during each experiment, and has veto power during any part of the proceedings. As an example of the dosages received, we were exposed during the entire high energy neutron experiments to only as much radiation dose as the general population receives from cosmic rays and natural background in the span of 2-3 days (about 1 millirad). Both principal investigators are included in a group of scientists who receive periodic eye examinations as part of a long-term study on cataract incidence in a population of radiation workers.

Helium Ion Beam

We are presenting preliminary descriptions of some very recent experiments with accelerated helium ions at the Berkeley 184-inch cyclotron, which have not been reported previously. These were designed with the hope that they would help localize the site of initial radiation interactions in the body that lead to light-flash observations and to determine the character and the efficiency of helium ion induction of visual sensations. We have earlier described the facilities at the biomedical exposure room, where monoenergetic beams of about 910-MeV helium ions are used in radiation therapy investigations (11).

Using a parallel beam of flux density of 10^6 to 10^8 particles $cm^{-2}sec^{-1}$ and a special arrangement shown in Figure 2, we adjusted the beam intensity to about 1 particle per second, representing 10^8-fold attenuation of the beam. The parallel stream of particles is restricted by an aperture 4 mm in diameter and to a maximum energy of about 240 MeV. Each particle is individually checked and recorded by means of pulse height analysis and coincidence counting. Appropriate beam tuning is used to exclude particles of unwanted properties. The position of the subject's head with respect to the particle stream is controlled by a head positioner to which is attached a tight-fitting positioning and dark-adaptation mask. The subject can be accurately aligned with respect to the beam position by means of X-ray diagnostic techniques. The depth of penetration of the particles can be changed at will by means of interposed absorbers. On a strip chart each particle is separately recorded as it arrives in time, along with any responses from the subjects, who can activate a hand-operated switch to signify visual identification of an event. A sound click can be triggered by each fast particle as it passes through the silicon detectors prior to entry into the subject; this may be used as an additional cue for the subject. Verbal instructions and reports from the subjects are recorded on magnetic tape, and closed circuit TV is used for surveillance of the subject during the experiment.

So far, the region in and around one eye of each of two subjects has been probed with a very small stream of helium ions, numbering in one experiment a total of 1500 ions for one subject (CT) and 1150 for the other (TB).

Encouraged by the earlier experiments with fast neutrons in which neutron fluences of $10^4 cm^{-2}sec^{-1}$ were used with about 25-50 visible flash events per second, we wished to establish initially whether or not a single helium ion passing through the retina of one eye could produce the sensation of a light

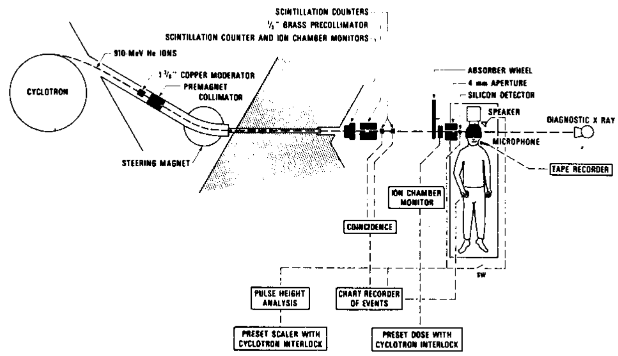


Figure 2:

Schematic of the arrangement used for human exposures. The exposures were carried out using exposure facilities developed at our Laboratory over the past several years for helium ion therapy. Special devices were added to allow exposure to individual helium ions at 0 - 250 MeV kinetic energy. The subjects wore dark-adaptation masks.

flash. The attempt to do this in a dark adapted subject was initially unsuccessful when an intensity of only one particle per second was allowed to cross the retina for periods of two minutes. In considering the possible reasons for this initial failure it became evident that we should be concerned not only with the possibility that a helium particle can cause an action potential in one or more visual cells of the retina, but also with additional psychophysical factors that may allow or prevent conscious registration of a very small light event in a milieu of background noise in the visual cells and of electrical noise in ganglion cells, synapses, and along the optic tract to the brain. Some degree of spatial and temporal integration is probably necessary before a given pattern of neural events will emerge into consciousness at a given instant. In the field of optical studies of light perception it is already known that near the photic stimulation threshold, the eye must be fixed in the dark and that a light stimulus must have certain spatial and temporal properties before it becomes observable (12). Specifically, Van Nes et al (13) have noted that the efficiency of seeing small light flashes of narrow angular aperture depends very sensitively on the time frequency of occurrence of such flashes as well as the spatial periodicity.

Our successful attempt at obtaining a subjective response from helium ion beams corroborates the importance of space and time summation in the response of the visual apparatus. When helium particles were allowed to cross laterally the central region of the retina of the left eye at random time intervals within an average rate of 10 per second, both subjects observed 2 to 5 flash events per second, including streaks with motion sense in the beam direction. A typical sequence of events is shown in Figure 3. At higher rates of arrival so many events were present in the visual field simultaneously that their identification became more difficult. At very high rates (> 100 per sec) only a single discrete flash was seen, and at very low rates less than 5% were recorded as visual sensations. Figure 4 gives an indication of recognition efficiencies at various particle arrival rates and reproduces particle arrivals and recognition signals from the subject in a typical 50-particle trial.

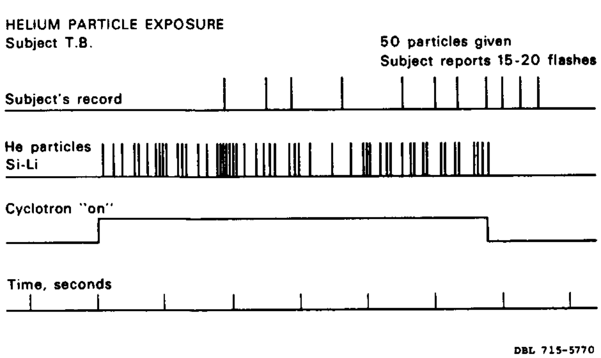


Figure 3:

A typical sequence of events in a helium ion exposure sequence. The arrival of each particle was recorded on a strip chart recorder as function of time. The subject signaled the appearance of light flash events by a manually activated **switch.**

When a 5 second burst of particles in a 4-mm-diameter pencil beam arrives at the retina at a random rate of 10 per second, the subject without any cues can readily identify their presence. However, a period of approximately 1 to 2 seconds appears to be necessary before clear recognition of individual events and descriptions of their characteristics became possible. From a background sea of dark grey-green fluctuation the rapid light events first emerge as faint flashes, and some time later particle events appear as brighter streaks and flashes. Some features of their structure and position can then be identified and described.

Attempts were made to enhance visual recognition of the flash events by sound clicks coincident with each particle as it passes the silicon detector and enters the head of the subject. The presence of this type of cue has made visual recognition more difficult than its absence. When helium particles entered the eye at a rate of about one per second, 4% were counted without sound clicks; in another run when sound clicks were present, no particles could be recognized (Figure 4). It is postulated that the signals from the sound clicks interfere with the central nervous system integration and conscious recognition of any visual events registered at the retina.

Oral warning or countdown at one or two seconds before the helium particle stream was turned on seemed to be helpful for the subject. Perhaps the "internal scanner" is placed on "alert" in this manner.

He IONS FLASH 240 MeV
Subject T.B.
Left eye, lateral position I, no absorber

Result of several runs

Rate	Events seen
1 per sec	4-6 per 100
10 per sec	30-40 per 100
30 per sec	20-30 per 100
>100 per sec	1 per 100

Run No. 5 No clicker

1 per sec	3 per 50

Run No. 6 Particle triggered clicker

1 per sec	0 per 50

DBL 715-5769

Figure 4:

Summary of several exposure sequences with subject TB.

The distribution of range penetrations of the helium nuclei was carefully measured before each set of exposures by means of phantom absorbers and silicon solid state detectors upstream and downstream from the absorber. With the aid of these data together with the intensity of particles and observers' reports, in various test runs it was possible to obtain some idea of the efficiency of detection of events. Events were recorded only when the central region of the retina in the posterior portion of the eye was in the beam. The size of the sensitive strip on the retina was about 8-mm on each side of the beam axis. When beams of several hundred particles were passed through the anterior portion of the eye (but behind the lens) or through the optic nerve posterior to the eye there were no flash or streak events. In this latter position, however, one observer saw a few "luminous cloud events," decaying relatively slowly in a few seconds. More work is necessary before the cloud type of event can be definitely attributed to a "neural light flash" event caused by helium ions as similar phenomenon have been observed during periods when the beam was off.

Figure 5 shows a schematic cross section of the left eye viewed from above in relation to the positions of various beams passed through it. Flash counts were attempted by the subjects at five different mean penetration distances attained by the use of absorbers. The graph indicates the depth-penetration curves as functions of absorber thickness for each of the five penetrations. The position of the eye for these could be only approximately determined from tissue stopping-power data and the subjects' reports as to the location of the light-flash events on the horizon. The frequency distribution of stopping particles is also shown.

In Figure 6 we have plotted the subjects' actual counts of light flash events when the particle rate was 10 per second against the counts of particles that penetrate to each depth. The table gives detection efficiencies for each of the five positions. It is somewhat surprising to find that particles arriving either at the center of the retina or several millimeters away are all counted at about the same efficiency of 40% to 45% by subject TB. We feel that the actual detection efficiency varies between 25% and 50% because the reliability of the experiment was not as good as indicated by these numbers. When the beam did not reach the retina (position V, Fig 6) no flash event was seen by the subject in a stream of 200 particles. During these experiments the subject did not know what particle range was being used. Apart from an oral announcement about 10 seconds before the stream of particles entered the beam line he had no cues of the times the beam was turned "on" and "off".

Streaks

Of several hundred events seen, about 25% were reported as streaks of various lengths. The subjects used a simple method to report the lengths of the streaks. They estimated what the length of the trajectory would be if it had been produced by a pencil of light at a meter distance from the eye (Figure 7).

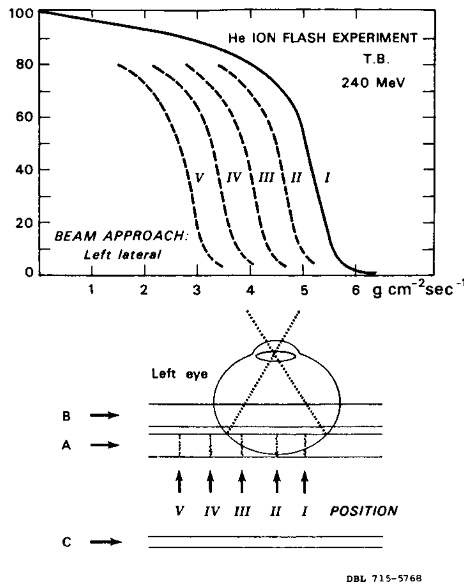


Figure 5:

The lower part of the Figure indicates beam positions A, B, and C where light flash exposures were attempted. Most events were observed in Position A. The upper curves are relative number-distance curves for the particles as determined prior to the experiment in a phantom. By insertion of appropriate absorbers, the depth of penetration was controlled to one of five penetrations (I, II, III, IV, V) in each test sequence.

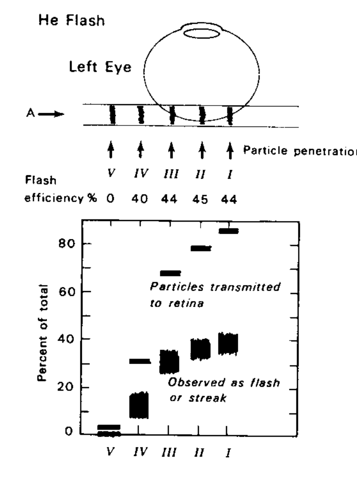
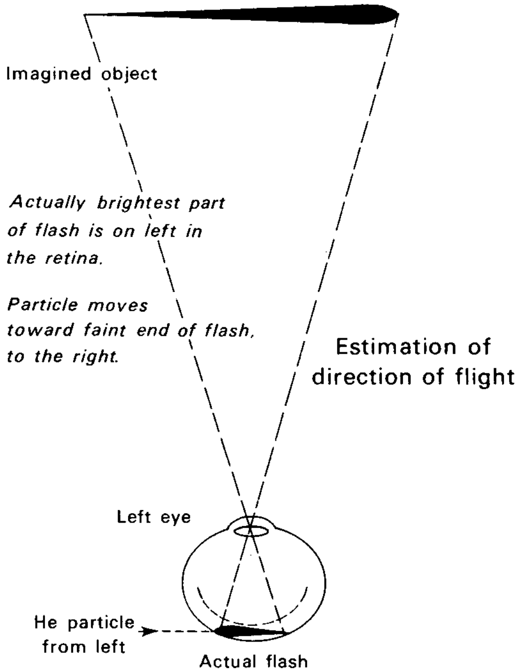


Figure 6:

The lower portion shows the percentage of particles transmitted to the retina at each of the five particle penetrations and the percentage observed as flash events. From such observations the "flash efficiency" was obtained for each exposure.



OBSERVER believes brightest part of track leading. Brightest part is on right. Hence particle is moving to right, a correct illusion.

Figure 7: DBL 715-5767

An attempt was made to explain why the observers coul attribute a direction of motion to the streaks (see text).

Persistence of the Light Flashes Observed

Most of the events observed appeared to have exceedingly brief lifetimes and left no after effect. A very few of the brighter white streaks, in the central portion of the retina did have a greenish after image, persisting for intervals of the order of 1 - 2 seconds for observer CT.

Dependence on Dark Adaptation

We have also separately shown that ability to observe the light-flash signals depends on the state of dark adaptation. In the course of the experiment and after many flashes were seen in the dark, a subject was re-exposed to room lights for 2 minutes and then dark-adapted again. His ability to see particle-induced light flashes gradually returned in a span of about 10 minutes, however, there was annoying, very persistent after image of the rectangular fluorescent light used in light adapting during this 10 minute period. In summary we have observed that helium ions, when they cross the retina, give rise to the sensation of light flashes, streaks, and "supernovae." Proton recoils and alpha particles produced by neutron interaction in the eye also give light flashes and streaks. These events are probably from ionizations and excitations in the path of the particles. The excitations are accompanied by emission of electromagnetic radiations in a broad spectrum of wavelengths. More refined work will be necessary to identify the physical events that actually initiate light sensation and the location of biological structures where primary interactions occur. It is interesting to speculate that the light-flash events may be related to some physical event in rods, perhaps initiation of action currents across membranes of the outer segments of rods. We believe that flash events may occur when several nearby rods and perhaps cones are affected simultaneously and in coincidence.

The helium flash events are not due to Cerenkov effects. Low energy helium ions, perhaps up to 50 MeV/nucleon (200 MeV) can cause flash events. It also follows that protons to about 10 MeV kinetic energy, and (in space) all heavier cosmic ray particles, probably with $Z \geq 6$, even at several hundred MeV/nucleon kinetic energy, can cause flashes.

We have also shown that the same events are seen with different efficiencies and with considerably different detail when the particle flux density changes. At very low or very high flux densities more than 90% of the flash events might be missed, whereas at an arrival rate of about 10 per second, about 40% are seen. The recognition of flash events depends on spatial and temporal integration in the nervous system. At the highest observed efficiency, about 40% of the particles passing through central regions of the retina are detected. Correlation of events observed in space with actual cosmic ray particle fluxes also depends on spatial temporal integration and it is possible that 5 to 20 times as many flash-causing events occur as the frequency actually reported by astronauts. An obvious answer to the efficiency of human detection of primary cosmic rays would be to conduct in space actual physical particle-identification studies during periods of human observation of the flashes they cause.

Most of the observed events can be accounted for by the assumption that the fast particles cause interactions in the retina particularly in the receptor layer. This is illustrated in Figure 8.

Magnified section of the RETINA
(not to scale)
Rod layer about 10 μ wide.

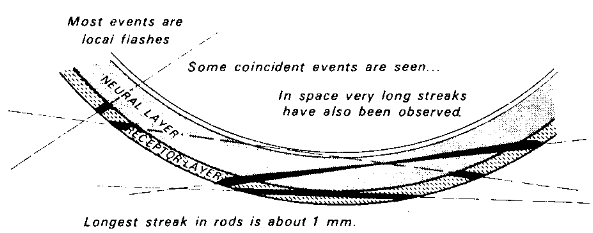


Figure 8: DBL 715-5766

A schematic section of the retina is given to illustrate how various observed events correspond to particles crossing the retina at various angles. Most events observed are local flashes. The manner in which streaks and segmented coincidences might be produced is also shown.

The receptor layer contains the outer segments of rods and cones with visual pigment.

We believe that grey or colored X-ray phosphenes are produced by diffuse interactions in the receptor layer.

Luminous cloud observations are not explained in this figure. They might be due to light that reaches the receptors from the neural layer or vitreous fluid.

From this estimation and refractive index of the vitreous humor one can estimate the length of the interaction on the retina. By this method the longest streaks had a path of about 1-mm in the retina, tangential to it, corresponding to a track length of about 5 cm, 1 meter away from the subjects When the curvature of the retina is taken into account, as well as an estimated thickness for its light sensitive part of 10 microns, it turns out that the longest unbroken straight path under these conditions is about 2 mm. We assume that only the part of a track that passes through the light sensitive layer of the retina is recorded. The depth penetration of particles is much greater than this path. It seems likely that at least the last several millimeters of a helium ion track can cause a light flash. If the retina should be sensitive to high energy helium ions as well as to low energy, we should have seen bisegmented tracks (coincidences). We have not been able to see such coincidences in any of these experiments, but more work is planned on this problem in the future. In space, quite long and intense light flashes were seen by several astronauts sometimes comprising as much as 55° aperture. In addition, about the right number of bisegmented tracks were reported to assume that many cosmic ray particles were able to elicit light sensation along several cm portion of their track.

Sense of Direction of Streaks

For a portion of the light streaks seen, the subjects reported very definite and correct sensations with respect to the direction of passage. Similar observations were reported in the low energy neutron experiments (10). Since the particles go through the retina in less than 10^{-11} second, one would not presume that normal light direction sensing mechanisms can recognize motion of the flash. At the present time the observations at hand are not sufficient to unequivocally establish for sensing the direction of travel of the particles. Nevertheless, for the purposes of discussion and further experiment, we suggest the possibility of a double optical illusion as an explanation for the recognition of direction. As we illustrate in Figure 7, the subject perceives a straight trajectory, in front of him, widening and brightening from left to right. This conveys a sense of motion in the same direction. Actually, in the retina, the track may be represented by a "thindown" due to the range distribution of its delta rays. It is assumed that more rods are affected on the left than on the right. The guess of movement to the right appears to be based on two kinds of mistaken judgement: (a) that the streak is in front not within, and (b) that it is brightest in its leading portion. Another explanation for motion sense in random directions was given by us for the neutron phosphene experience (1).

Supernovae

Each subject saw a few isolated events that had the appearance of a "supernovae", as defined by the astronauts. Such bright flashes with fuzzy margins were observed at absorber settings when most of the particles were near the end of their range, where the rate of energy is highest. The center of these events appeared to be colored blue, and in one case a brief flickering of blue and red. Similar events observed in space were brighter and larger than those observed by us, according to discussions with Apollo 14 crew. We used a variable light source of various shapes to compare the astronauts' experiences with ours.

Future experiments are planned to test the responses to interactions of accelerated particles with brain centers. Possible regions of interest are in the lateral geniculate bodies and in the occipital cortex at the calcarine and parieto-occipital fissures. Unfortunately there are no accelerated particles of ions heavier than helium available with sufficiently high penetration to test visual events caused by them. Exploitation of nuclear particles for exploring central-nervous-system function depends on constructing heavy-ion accelerators capable of accelerating particles with various atomic numbers to energies of several hundred MeV/nucleon.

The observation of light flashes in space flight and in accelerator beams has posed many scientific questions that await answer. Among these is the magnitude of deleterious effects that individual particles might cause in the retina and other regions of the nervous system (e.g., cardiac pacemakers, hypothalamus). Research has been initiated to answer some of these problems.

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